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Why Do We Fail in Aging the Skull From the Sagittal Suture?

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ABSTRACT The controversy over the reliability of ectocranial suture status (open vs. closed) as an age estimation stimulated the pursuit of Meindl and Lovejoy's suggestion (Meindl and Lovejoy [1985] Am. J. Phys. Anthropol. *68:*57– 66) for large scale analysis. The extent of the sagittal suture closure was assessed in 3,636 skulls from the Hamann-Todd and Terry collections. The debate over whether cranial suture ossification represents a pathologic or an age-predictable pathologic process also stimulated a comparison with age and two stress markers, hyperostosis frontalis interna and tuberculosis.

Sagittal suture closure was found to be age-independent and sexually biased. The wide confidence intervals (for age) appear to preclude meaningful application of suture status for age determination. No correlation was found with the tested biologic stressors. Am J Phys Anthropol 103:393–399, 1997.

Reliable skeletal aging (on the basis of cranial suture closure stages) has been one of anthropology's more ambitious interests (Montagu, 1938). Although earlier (e.g., Todd and Lyon, 1924) and later (e.g., Masset, 1989) studies suggested that this was probably unachievable (at least for the accuracy required for forensic applications or paleodemography), during the past 50 years there have been persistent efforts to achieve this goal [mainly by modifying earlier works, such as that of Todd and Lyon (1924)]. The main conclusion of Todd and Lyon (1925a, p. 39) that "ectocranial closures are . . . not so reliable as an age indicator" and subsequent works of Singer (1953) and McKern and Stewart (1957) did not weaken efforts to find the "secret" aging formula [(e.g., Workshop of European Anthropologists: Recommendations for age and sex diagnosis of skeletons (J. Hum. Evol. 9:517–549, 1980)]. Although Perizonius (1984) seemed to put the issue to rest by showing that most ectocranial sutures manifest a very low, non-significant correlation with age, its revival was sparked soon after by Meindl and Lovejoy (1985), who suggested a shift from the sutures of the vault to the latero-anterior sutures.

Despite their low prediction value, suture closure formulae are still among the most popular method for aging in forensic and anthropological studies. The hunch that "there is something in it" may derive from the long history of the subject, going back to Vesalius's time, which makes it a traditional

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TABLE 1. Spearman rank correlation coefficients of the closure stages in the various suture sections with age in 20–49 and 50–99 subsamples (data from Perizonius, 1984)

Ectocranial	20–49 years	50–99 years	Endocranial	20–49 years	50–99 years
Midlambdoid	0.36–0.42	No correl.	Full sagittal	0.43–0.56	No correl.
Lambda	No correl.	No correl.	Left lambdoid	0.44	No correl.
Obelion	No correl.	No correl.	Left coronal	0.59	No correl.
Anterior sagittal	No correl.	No correl.			
Bregma	0.30	No correl.			
Midcoronal	No correl.	No correl.			

research obsession. Maybe, as Meindl and Lovejoy put it, it is just a matter of our "prejudice" and "further refinements and blind tests may allow this indicator to once again achieve an important and functional role in age determination in both forensic and archaeological applications" (1985, p. 66). Are Meindl and Lovejoy right? Is it just a matter of "refinements"? In "Standards for data collection from human skeletal remains" (edited by Buikstra and Ubelaker, 1994), in the section on aging, such a refinement approach is presented: several aging methods, based on different cranial sutures (Baker, 1984; Mann et al., 1987; Meindl and Lovejoy, 1985; Todd and Lyon, 1924, 1925a,b,c), were combined to predict age. This "refined" method, however, ignores the fact that correlation between the recommended areas for inspection (along the cranial sutures) and age are very low (Table 1). These new "standards" may still turn out "old results."

Use of suture closure as an age estimate is predicated upon the hypothesis that suture closure is part of the aging process. Yet, when suture closure patterns were first studied at the beginning of this century, there were two schools of thought (British and Italian) on this issue. The British school maintained that sutural ossification and cranial immobility were normal conditions, whereas the Italian school maintained that they were pathologic in mature human adults (Sperino, 1931). In time, probably due to the increasing prominence of the English language in the scientific literature, the British approach toward suture closure became the dominant model in physical anthropology (without actually testing that hypothesis).

The working hypothesis in the current analysis is based on Cohen (1993, p. 594): "Patency is the original condition evolutionarily and ontogenetically; it is fusion that needs to be explained." The suggestion that order of sutural fusion is determined (in different animals) by growth patterns and differential stresses (Herring, 1993) requires further assessment. In suture biology studies (Persson et al., 1978; Moss, 1958, 1960; Persson and Roy, 1979), vascular, hormonal, genetic, mechanical and local factor contributions have been suggested, but not in any quantifiable manner (Cohen, 1993). As cessation of growth does not necessarily lead to suture fusion and suture closure does not fully limit growth, it is hoped that studying demographically characterized skulls might provide further insights.

Meindl and Lovejoy (1985) suggested that large scale blind testing of suture status in age assessment was needed. The current study was undertaken in pursuit of that suggestion, by examining the variation in extent of suture closure in the largest collection of skeletons of known age at death (Hamann-Todd collection), and validating those findings in a second, ethnologically comparable population (Terry collection). The relationship of closure to aging (growth) was assessed through age cohort analysis, while the correlation with chronic stress was determined indirectly. Sources of potential biologic stress were examined. Tuberculosis (TB), as the major early 20th century chronic urban stress, was used as a systemic stress marker and hyperostosis frontalis interna (HFI) was used as a marker for cranial reactivity/stress to gain insights to aging vs. non-age-related factors in suture closure.

MATERIALS AND METHODS

The human skulls selected for this study were from two collections: the Hamann-Todd collection, housed at the Cleveland

Museum of Natural History, Cleveland, Ohio, and the Terry collection, housed at the National Museum of Natural History, Washington, D.C. The distribution of the two samples by age, sex and phenotype appears in Tables 2 and 3. The total sample consisted of 3,636 skulls. Observations were made on the sagittal suture only. The sagittal suture was chosen as it is the only "end-to-end" type suture in the calvaria (avoiding "pseudo-closure" due to overlapping of bone, as in frontal over parietal bone), and because its location at the midline neutralizes it from biomechanical influences (Kanisius and Luke, 1994).

Standard aging methods based on suture closure make use of two arbitrary assumptions: 1) that the different degree of suture closure (usually four stages) represents a normal progressive process, and 2) that different ontogenetic processes operate in different segments of the same suture (otherwise, why divide them into segments?). Not only do these assumptions have no factual basis, their application is very subjective: the division between segments of the same suture are not clear cut in many skulls. More than 20% of skulls do not follow the "classic" pattern of sutural segmentations. The definition of the four degrees of closure is also open to wide interpretation. For example, stage 2 (=significant closure) is defined as "a marked degree of closure but some portion of the site is still not completely fused" (Buikstra and Ubelaker, 1994), but what is meant by "marked degree" and "some portion"? How are these things measured?

To avoid preconceived notions about suture closure and to minimize observer error, conditions (not "stages," which implies progression) of sutural closure were defined metrically, as follows: Suture condition X = [sum of length of open sutural segment/total suture length] × 100 (measurements carried out with tape). "Open" was defined as absence of bony ridges transversing the suture from one parietal bone to the other. Five sutural conditions were defined, as follows.

1) Totally closed (TC): no signs of the sagittal suture were observed on the ectocranial surface, from bregma to lambda ($X < 2$).

TABLE 2. The population studied, sex and racial phenotype distribution (age combined)

Population phenotype	Terry collection			Hamann-Todd collection		
	Male	Female	Total	Male	Female	Total
American blacks	533	369	902	568	173	741
American whites	458	312	770	1074	143	1217
Others	5	1	6	0	0	0
Total	996	682	1678	1642	316	1958

TABLE 3. The population studied, sex and age distribution

	Terry collection				Hamann-Todd collection		
Age	Male	Female	Total	Age	Male	Female	Total
20–25	36	29	65	20–25	129	44	173
26–35	123	64	187	30–35	232	55	287
36–45	148	80	228	40–45	393	61	454
46–55	184	104	288	50–55	379	55	434
56–66	213	109	322	60–65	280	37	317
66+	206	239	445	70+	229	65	294

2) Partially closed (PC): less than 10% of the suture length was open ($2 < X < 10$).
3) Totally open (TO): the suture line was clearly visible with almost no interruptions along its entire length, from bregma to lambda. Minor closure at the area of the parietal foraminae was ignored ($90 < X \leq 100$).
4) Partially open (PO): between 10% and 90% of the suture length was open ($10 < X < 90$).
5) Premature suture closure (PMSC). This condition should be distinguished from pathological closure, which occurs very early in life (5 years or earlier), and which is characterized by sutural ridging (i.e., scaphocephally). In the PMSC category all skulls in which the sagittal suture was closed after the age of 5 years, but before 18 years, were included. Usually, they do not show any minor or any gross deformation, and more importantly, do not have sutural ridging.

To examine for possible genetic or pathologic (metabolic) components in suture closure, a particular type of suture obliteration was designated: the "Double Y" closure, a situation in which both the coronal and the lambdoid sutures are totally open while the sagittal suture is totally closed. The relative

frequency distribution (by age, sex and ethnic origin) of the "Double Y" closure condition was calculated. The relationship between different suture conditions and medical conditions (HFI and TB) were examined by Chi square test.

RESULTS

The results are presented in Tables 4 to 7 and Figures 1 and 2. For males, Table 4 and Figure 1 show that the frequency distributions of suture categories (conditions) were virtually similar in all age groups after age 35. This eliminates the basis on which most of the aging methods, based on cranial sutures, were established, i.e., the assumption that suture closure is an ongoing, continuous transition from open to closed sutures. The sutures' condition, i.e., TO, TC, PO, or PC, appears determined by the age of 35 years. Transition from one category to another after age 35 was rare. With all the reservation of a cross-sectional study, progressive changes could occur only within the PO category, where suture closure extent can vary from 10% of the total suture length to almost 90% of its length. Total closure, however, would probably not occur.

Females manifest a different pattern of sagittal suture closure (Table 5, Fig. 2). The frequency of open suture skulls (TO) decreased steadily with age, as that of the closed suture skulls (TC) increased. Relative frequency of the PC suture condition remained constant with age, while the PO condition gradually increased until age 40–45, and then remained constant around 30%. In all age cohorts, there were always significantly more females with open sutures than males, until age 65 years (Tables 4–6). The relative frequency of premature suture closure did not change significantly with age, as expected (df = 5, $\chi^2 = 9.181$, $P = .1021$) (Table 7).

The possible racial aspect of suture closure was examined via the differential frequency of the "Double Y" type suture form in the sampled population. Our data clearly show that this type of suture condition was significantly more common in American black males (5.06%) than in American white

TABLE 4. Distribution (%) of sagittal suture closure degree in six age groups (5 and 10 years intervals,[1] male only)

Age	TC	PC	PO	TO	N
20–25	18.3	3.3	22.2	56.2	153
30–35	33.1	7.2	28.5	31.2	263
26–35	29.6	3.7	25.0	41.7	108
40–45	24.6	8.3	42.7	24.4	492
36–45	24.3	8.1	37.8	29.8	148
50–55	27.2	8.0	41.5	23.3	467
46–55	27.1	7.6	40.7	24.4	184
60–65	29.1	10.4	37.4	22.9	405
56–65	29.6	9.4	36.6	24.4	213
70+	26.6	7.6	38.9	26.9	368
66+	30.1	7.3	36.9	25.7	206

[1] Ten-year interval only for Terry collection.
TC, totally closed; PC, partially closed; PO, partially open; TO, totally open.

TABLE 5. Distribution (%) of sagittal suture closure degree in six age groups (5 and 10 years intervals,[1] female only)

Age	TC	PC	PO	TO	Total
20–25	14.1	4.7	9.4	71.8	64
30–35	17.2	5.2	17.2	60.3	58
26–35	12.1	6.9	20.7	60.3	58
40–45	12.6	5.3	33.7	48.4	95
36–45	16.2	5.0	30.0	48.8	80
50–55	13.9	7.7	31.8	46.6	129
46–55	16.3	7.7	30.7	45.3	104
60–65	27.1	6.5	28.7	37.7	122
56–65	25.7	3.8	32.0	38.5	109
70+	30.3	6.4	30.7	32.6	264
66+	30.5	5.5	31.4	32.6	239

[1] Ten-year interval, Terry collection only.
TC, totally closed; PC, partially closed; PO, partially open; TO, totally open.

TABLE 6. Statistical differences (χ^2) between male and female in relative frequency of totally open (TO) suture condition by age groups (df = 1)

Age	χ^2	*P*
20–25	4.648	.0311
30–35	17.451	.0001
40–45	22.671	.0001
50–55	26.714	.0001
60–65	6.970	.0083
70+	2.390	.1221

TABLE 7. Frequency (%) of premature suture closure cases by age group

20–25 years	30–35 years	40–45 years	50–55 years	60–65 years	70+ years
2.0%	3.4%	2.0%	2.5%	2.7%	0.7%

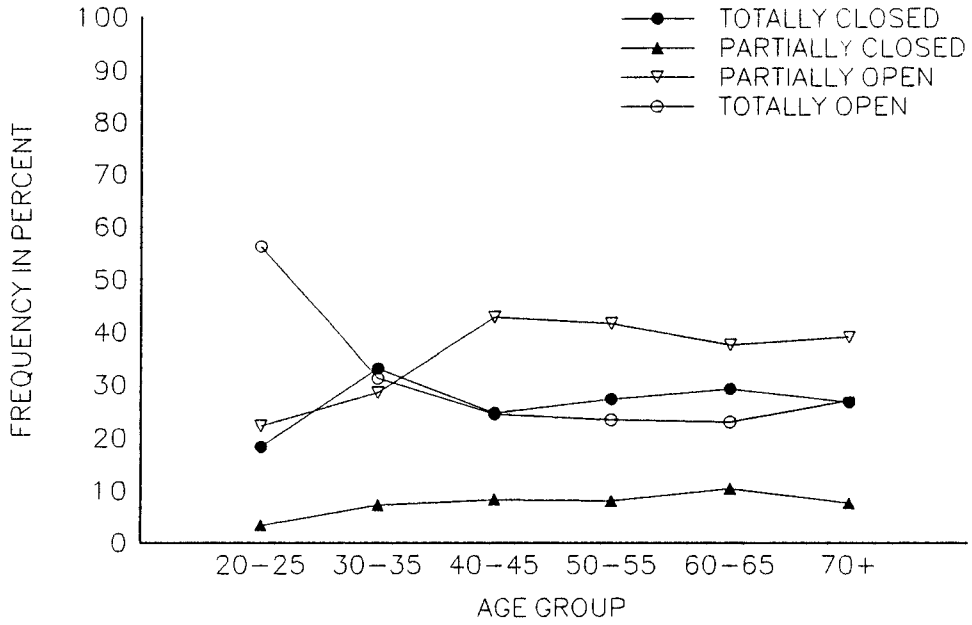

Fig. 1. Distribution of sagittal suture closure category in males, with age.

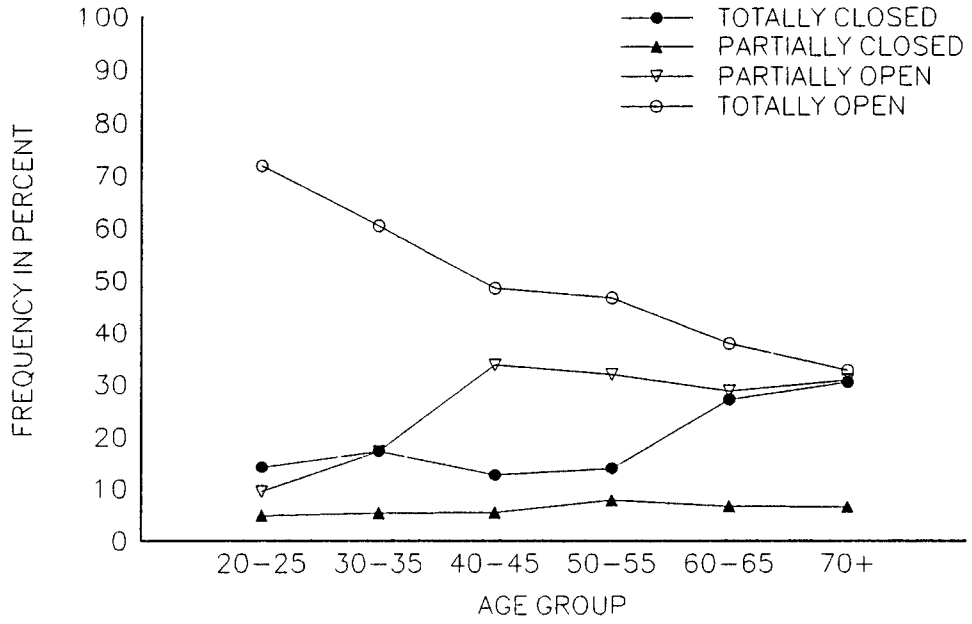

Fig. 2. Distribution of sagittal suture closure category in females, with age.

males (0.04%) (df = 1, $\chi^2 = 17.593$, $P < .0001$). Among females, the differences were less dramatic, 1.63% among black females and 0.96% among white females (df = 1, $\chi^2 = .578$, $P = .4469$).

When data were corrected for sex and age, no association was found with the two stress factors studied, HFI (df = 3, $\chi^2 = 5.921$, $P = .1155$) and TB (df = 3, $\chi^2 = 1.124$, $P = .7713$).

DISCUSSION

A study of 3,638 skulls of known age failed to substantiate any reproducible relationship between age and extent of suture closure. This apparently precludes forensic application and severely limits its value in paleodemography. Efforts to improve the predictive value of the suture closure aging method by extending the age groups (i.e., 25–44; 45–70 years) do not seem beneficial. For example, a skull with totally obliterated sagittal suture has almost the same probability of falling into either age group (see Table 4).

Immutability of suture morphology with age (Kanisius and Luke, 1994) and the high frequency of the "Double Y" closure type pattern in American black males (this study), and reports of autosomal dominant and recessive patterns of premature suture closure (craniostenosis) (Cohen, 1986, 1988) suggest a genetic predisposition for suture closure in general. If so, one would expect to find a large variation in frequency of cranial suture closure patterns among ethnically diverse populations. A hint of such a possibility can be found in the study of Kanisius and Luke (1994), where differences in suture pattern between Europeans and Australian aborigines were noted. This may be the first, although indirect, evidence to a major role that genetics plays in determining suture pattern and closure.

Suggestion of a genetic predisposition raises the question of biologic adaptation (for different suture patterns). In the absence of relevant data, we can only offer thoughts on this issue: Open sutures may increase skull efficiency in absorbing related mechanical stresses. Given the frequency of skull trauma in historic (e.g., Walker, 1989) and modern populations (e.g., Jagger et al., 1984), open sutures may reduce impact stresses, while the interlocking nature of the sutures prevents actual bone separation. This potential benefit must be weighed against increased strength related to suture closure. The latter, however, may result in premature limitation of skull (and brain) growth; as Herring (1974) put it, "In evolutionary terms, the value of strengthening and buttressing the skull by suture fusion must be weighed against the danger of premature limitation of important growth." With this in mind, selection may favor an intermediate stationary state (PO, PC).

In summary, suture condition appears to be an age-independent, sexually biased phenomenon, with minimal identifiable stress (biologic) association.

CONCLUSIONS

1. The sagittal suture cannot be used for aging the skeleton.
2. Although cross-sectional in nature, suture obliteration patterns (totally open, totally closed, partially open, partially closed) are not temporary progressive stages on an age scale, but rather independent permanent phenomena.
3. Some suture closure patterns are genetically inherited.
4. Females and males manifest different suture closure patterns.
5. In all ages, the relative frequency of the "totally open" category is higher in females than in males.
6. The medical conditions (HFI, TB) examined in the present study are not associated with a suture closure condition.
7. Suture closure is neither a pathological phenomenon nor the result of normal aging process.
8. Both the Italian and British schools were probably incorrect in their conception of the cranial sutures.

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